RENSSELAER POLYTECHNIC INSTITUTE

KNOWLEDGE AND THOROUGHNESS

1824

Rensselaer Polytechnic Institute

Troy, New York

R.P.I. Technical Report - MP-13

INSTRUMENTATION STUDY OF PRIMARY NAVIGATION SYSTEM FOR A MARS ROVING VEHICLE

Jeffrey V. Wilson

NASA Grant NGL 33-018-091

Analysis and Design of a Capsule Landing System and Surface Vehicle Control System for Mars Exploration

MAY 1970

Rensselaer Polytechnic Institute
Troy, New York

CONTENTS

contents cont'd.

Page

LIST OF FIGURES

ACKNOWLEDGEMENT

The author wishes to express his gratitude to Dr. C. N. Shen for his advice and assistance as Faculty Advisor during the preparation of this work. The patient critique of Mr. R. E. Janosko was also appreciated.

ABSTRACT

In the latter part of this decade, this country intends to send an un-manned roving vehicle to explore the surface of the planet Mars. In order to complete its mission, this vehicle must be capable of long-range autonomous navigation on the surface. The purpose of this report is to develop and discuss the instrumentation of such a primary navigation system.

The instruments themselves are found to require several unique applications of existing sensors and in some instances the desired system requires sensors not presently in existence. Features of the desired system include a determination of an inertial frame with origin at the planet center, establishment of a reference platform on the vehicle without use of conventional gyroscopic stabilization, a computation scheme for enabling a satellite to provide the vehicle with location data for targets beyond the vehicle's horizon, a surface dead-reckoning scheme for continuous tracking of vehicle position and a proposed flow diagram to combine all of these systems to provide the best possible position information.

Instrumentation considerations are shown to influence orbit selection, areas and time of exploration, and to some extent basic vehicle configuration. New instruments are proposed to fill the information gaps identified and a discussion of the overall accuracy of the final configuration is included.

1. BACKGROUND. As part of the basic schedule for exploration of the planet Mars, an unmanned roving vehicle is to be landed on the surface in the late 1970's.[1] This mission is to follow the two stationary surface probes of Project Viking and the keynote of the mission is to be vehicle movement to several selected areas on the surface for exploration. Specifically, the mission requires an autonomous system capable of both planning and executing excursions of many miles over the surface toward a given target. Of course the system will have backup modes involving various degrees of control from earth, but the basic system must be capable of performing the following basic functions if it is to meet the mission goals:

a. Find, identify, and locate the desired target in some useable reference frame.

b. Locate the vehicle in the same reference frame, thereby establishing a desired direction of travel - a basic navigation vector.

c. Sense the local terrain and determine the optimum path to actually follow while negotiating the distance to the target.

d. Actually "drive" the vehicle along the intended path.

The major components of the system include the vehicle itself, an orbiting satellite and earth-based computation, control, and monitor facilities.

Project organization on campus has divided the overall system so that parts (a) and (b) are treated as the primary long-range navigation functions while parts (c) and (d) comprise the secondary or guidance system. This paper is concerned with the implementation of the primary system - determination of the navigation vector. The basic system for utilizing the orbiting satellite to assist the vehicle in computing this navigation vector was originated by Dr. C. N. Shen. This system was then designed and is now being refined by Mr. R. E. Janosko [2], assisted by Mr. Chen [3]. This basic design combines various measurements made by the satellite and the vehicle in a fitting and filtering process to independently determine the position of the vehicle and target in an inertial frame.

2. OBJECTIVES. With this as background then, it may be stated that the topics of this paper are the instrumentation of the basic satellite update system and the integration of this scheme into an overall navigation system. The specific objectives are as listed below:

(a) Determine if the system required measurements could be obtained with currently available or predictable sensors.

(b) If sensors are available, study the implications for the physical assembly of the system, effects on mission profile, and general limitations imposed.

(c) If sensors are not available, either design new ones or provide feed-back to the other members of the design team to allow possible modification of the basic system design.

(d) For a final sample choice of instruments, discuss component and system accuracy.

During the course of this work, considerable effort was also directed toward establishing useable reference frames for the system since it was discovered that this problem was closely coupled to the instrumentation problem in general. With these basic objectives in mind, the first effort of the work was to survey the nature of the mission and establish the general requirements which all the instruments must satisfy in order to qualify for consideration on the mission.

3. GENERAL INSTRUMENT REQUIREMENTS. For a trip to Mars, the instruments and associated computational hardward must of course be as light, simple, and dependable as possible because the entire system is to be automatic. They should be adaptable to the environment of outer space and the bleak surface of Mars. There will in general be no manual assistance available to resolve singularities, establish initial course orientations and make decisions. The vehicle equipment must establish the reference frame from an initially partly dis-oriented position and must be capable of relocating reference points such as the target or the satellite rapidly if the system breaks track. System components on board the vehicle must be able to survive and function in the presence of random vehicle accelerations and shocks, as it traverses rough terrain. This condition lead to efforts to do without the conventional gyro-stabilized platform with accelerometers for establishing reference frames and sensing vehicle movement. Effort was instead channeled toward systems tracking exterior objects and local vertical for the reference frame, using a surface velocity sensor plus satellite and solar observations for position data. Under limited conditions this system showed some promise, but has serious failings in general applications. As previously mentioned, the environment of the system

on the planet's surface will be distinctly hostile to automated navigation. Detailed information about the atmosphere through which the sensors must operate is very scarce, but it is generally known that the surface has a thin (3 to 18 millibars), turbulent atmosphere with winds of several hundred miles per hour not uncommon[4]. Such winds may produce violent dust storms and highly erratic conditions of optical and radio propagation. While high-altitude observations should be generally reliable, any measurement near the horizon is likely to be very suspect because of atmospheric effects. Those low-altitude observations are also hampered by the rugged Martian terrain, as any track which takes the vehicle near large obstacles would likely block a large portion of the near-horizon view, (see section 7B for a discussion of the implications of this limited field of view). The problem is even further complicated by the fact that the desire to use local vertical as one major component of the system makes the high-altitude observation of other bodies or reference points difficult because of the singularities involved. Hence the observations which are best from an instrumentation point of view are the worst from a geometrical point of view, and vice versa. This conflict affects other decisions such as the choice of landing sites, time of year for the exploration, types of orbit used, and certainly the overall system accuracy. The external components of the system must also be made impervious to the sand, dust and wind on the surface. This is a trouble spot for optics. Time is also a consideration in instrumentation. Although the mission will be on the planet for several weeks or months, the instruments involved in the satellite-assisted computations must react quickly enough to get good readings during each pass of the satellite.

This is especially important for such items as the meridian transit observation of the sun discussed in section 9, which happens only once each day, and for the satellite update of position, which happens only once every 2 to 12 hours, and has a duration of from 1 to 8 minutes. The target-finding system in the satellite can only operate during the hours when the target is in daylight and in view of the satellite, which may be only once or twice a day. Of course, once located a targets' position may be recorded and since the target does not move geographically, it need not be continually tracked to have the system function. Note that this daylight requirement applied only to a natural, non-radiating landmark on the surface such as a crater, mountain or other feature. If recognition and tracking of such features proves impossible, or would cause a disproportionate amount of development effort, an alternative technique would be to drop radiating beacons in the general vicinity of desired features, which could then be tracked and located at long range by the satellite and at short range by the vehicle itself.

It should be noted here that although the system sensors are the instruments which find most of the new and unique problems in this system, the basic communications equipment and computer designs are by no means trivial. The communications equipment would likely consists of a short range radio with omni-directional antenna for the vehicle's use in sending all its data directly to the satellite for relay, a major transmitter with high data and considerable storage capability in the satellite, and the usual large array of receivers and transmitters on earth for control and monitor functions, (the Deep Space Network)[5]. A second transmitter on the vehicle for direct transmission to earth is omitted here to provide more weight, space and power for vehicle propulsion equipment, but could be added if higher data rates, more reliability, or a backup mode were desired. The basic computer scheme of reference(6) is used as a format here. The most significant aspect of this technique is the use of a master sequencing center to optimize use of limited computer facilities for a wide variety of functions. It is this area which is affected perhaps more than any other by the requirement for the system to be autonomous. On all previous space missions the equipment has consisted basically of either one very specialized subsystem or a group of subsystems which were then coordinated by our most advanced sequencing system, a pilot. This mission will be the first time man has sent a major logic unit beyond the range of effective real-time control from earth so it is especially important that all sensors be as reliable as possible. A failure of the system's autonomous movement capability cannot be effectively counteracted by control from earth because of the lengthy time delay for radio communications and the mission would be reduced to little more than a repeat of the Viking probes. Reliability then is a must for all parts of the navigation systems, both primary and guidance. Although it is true that in this case a man's life does not depend on these sensors, a lot of taxpayers' money does, as might the future of any intended major excursion to other planets.

4. ORGANIZATION OF THE ANALYSIS. Navigation is all relative. In this case, the navigation problems are even more difficult because the system not only has to function

in relative terms, it has to decide what it is going to be relative to. Since there are may choices available, one of the primary tasks of an instrumentation analysis must be to separate the references which can be sensed and measured with some degree of facility from those which can't. Once this is done, an orderly process for using these references to form frames for calculation must be established. In this instance, Dr. Shen and Mr. Janosko had established a proposed procedure when the study was begun [7] so the objective was to find a way to instrument it. This approach revealed several difficulties in the basic system of reference frames, so in classic engineering fashion the original proposed solution was revised [2] and the instrumentation study repeated. The final combined system will be used as the basic format for this paper, beginning now with a discussion and definition of the various frames which are established and utilized by the system and then proceeding to the specific instrumentation of each frame. Following this will be a discussion of the implications of this system on overall mission profile.

5. ESTABLISHMENT OF REFERENCE FRAMES. The first and most basic reference frame used by the mission is the inertial frame used by the satellite itself during the transit to Mars. This would most likely be the conventional system currently in use in which the satellite itself is instrumented with star trackers to check the alignment of the entire package inertially. The satellite itself is considered the stable platform and is oriented as required by gas jets or some similar device. It is this basic inertial frame which is used during alignment for trajectory corrections, orbit insertion, and recursive unknown landmark navigation

schemes[8] to accurately determine the satellite orbit in space. Note that the unknown landmark navigation would require stored information about the movement of Mars in space if the desired trajectory is to be computed with respect to the stars (inertial space). The actual alignment of the orthogonal axes used by this system is unimportant to the primary navigation system because the major computational frames to be used are centered at the geocenter of Mars, as will be shown later. This basic satellite frame, called the S-frame, does not enter into the calculations directly but its accuracy does affect the system because the S-frame is used to determine the satellite orbit and also its position in that orbit as a function of time[2]. Several other frames are then established with respect to that orbit, and the position in orbit is used directly in the Janosko computations for target and vehicle positions.

To proceed with the details, the objective is to establish an inertial frame centered at the geocenter of Mars with one axis aligned with the spin axis of Mars and the other two axes in the plane of Mars' equator. This is done in the following fashion (see figure (1):

A. The orbit of the satellite is determined in inertial space. This implies that the vector Ic, (aligned with the orbit momentum vector $\overline{h}$), and Ia, (the direction of the semi-major axis), are know, with Ib being the cross-product.

B. The orientation of the axis of Mars and its equator are known inertially as a function of time. It is known that the center of Mars is one focus of the orbit, so that the Iabc frame is centered at Mars geocenter.

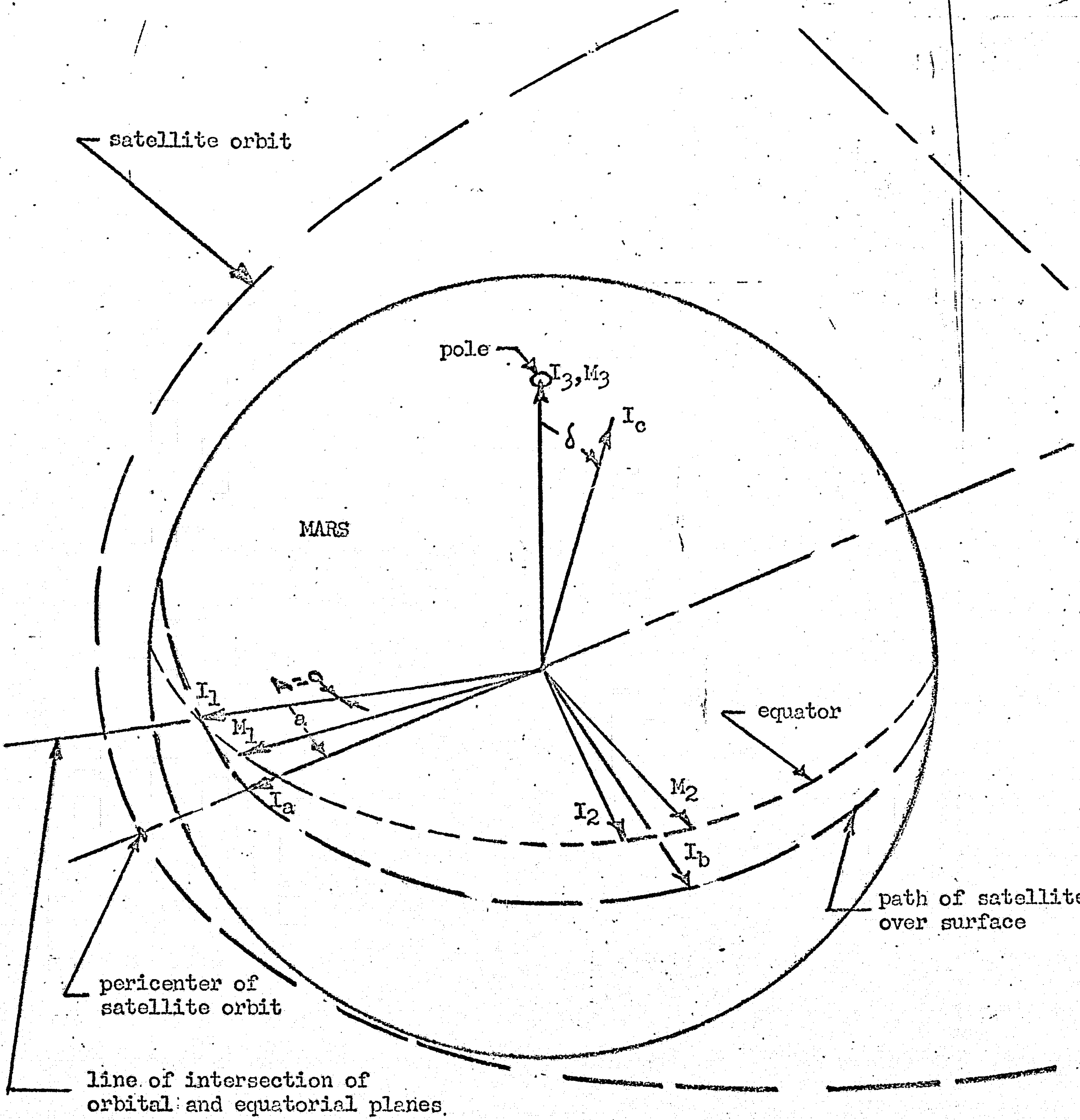
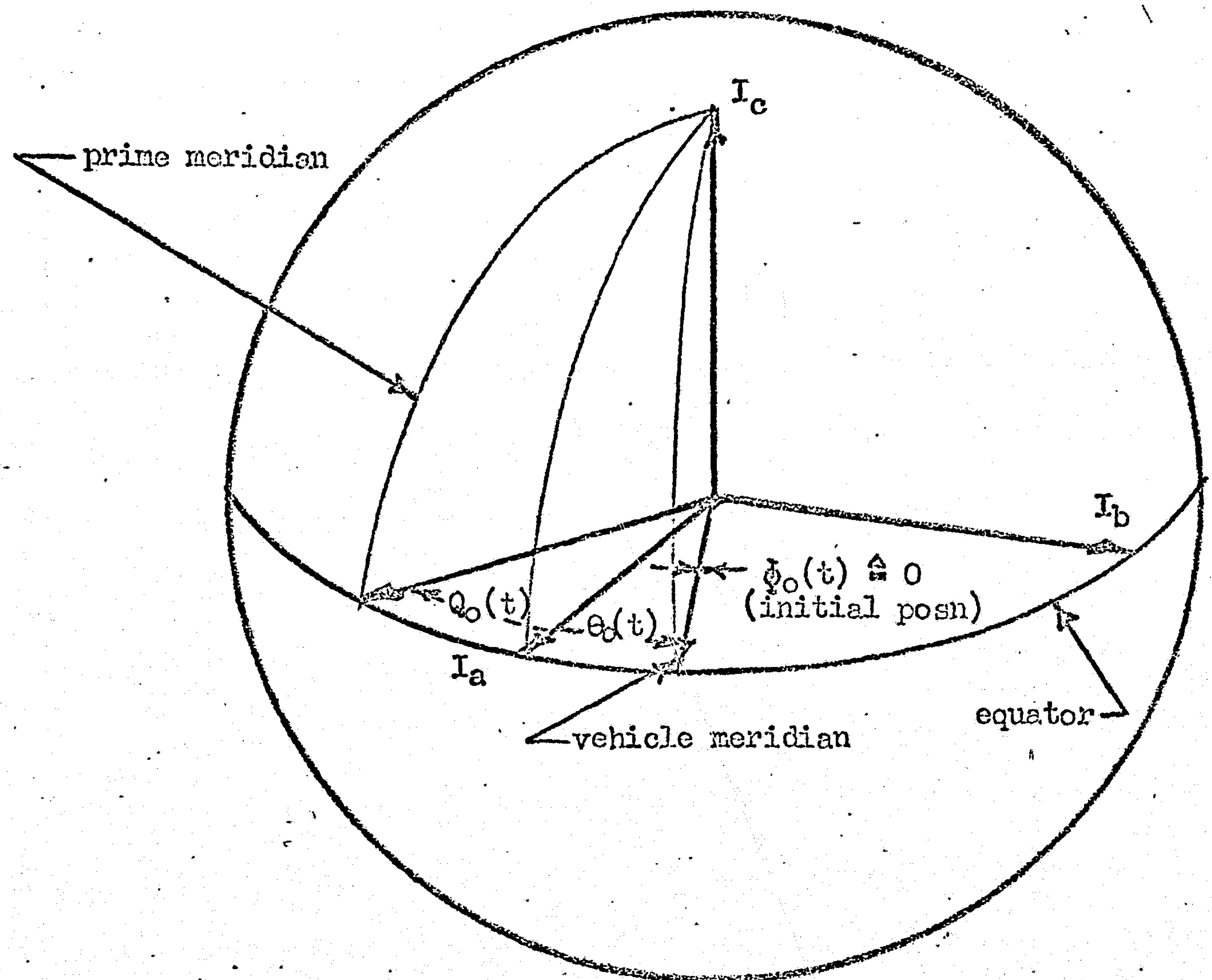


figure (1) Martian Reference Frames

C. From this the line of intersection of the plane of the orbit and the Martian equatorial plane may be determined, which amounts to determining angles α and δ. Again using the spin axis as one axis, the I_{123} frame is generated. This is quite analagous to the proceedure used in establishing the convention heliocentric inertial frame [9]; Mars equatorial plane corresponds to the plane of the ecliptic, the satellite orbital plane corresponds to earth's orbital plane, and the line of intersection, I_1, corresponds to the line of the vernal equinox.

D. From this position in the classic Euler angle description, one describes the motion of a body in the I_{123} frame by three angular rotations which give the inclination of the orbit to the reference plane, (δ), the displacement, (A), of the line of intersection of the orbit with the reference plane (called line of nodes) from the I_1 axis, and then the angle from the line of nodes to the semi-major axis of the orbit, (α). Note that the satellite orbit itself may now be defined in terms of the frame it helped generate. Simply, $\alpha=\alpha$, $\delta=\delta$ and $A=0$. That is, the "line of nodes" of the orbit and the line of intersection used to form I_1 just happen to coincide. But this is not really essential. The important part is that by comparison of two accurately established planes and one known spin axis an inertial frame may be derived which is centered at Mars geocenter and therefore translates through space with the planet.

E. The final step in this particular derivation is to establish a Martian geographic frame. Fortunately this is quite easy since the I_{123} frame is related to a conventional latitude-longitude frame by only a single rotation. Figure (2) shows three possible measures of a vehicle's "longitude" on the surface. There is a geographic reference grid which has been defined for Mars by simply setting the optical center as viewed from earth at some time zero as the "prime meridian", and then keeping track of its position by integrating the known rate of rotation of the planet.[10] This is both too inaccurate and too awkward for the vehicle or satellite to use. Instead, the initial landing position of the vehicle may be designated zero longitude and then movements measured from that meridian. Of course the vehicle may be referenced to familiar land marks in the old system by comparing the vehicle's position and that of the prime meridian in the I-frame at the same time, noting that from that time on the sum of the angle between the Martian prime meridian and I_1,$(Q(t))$, and the angle between the vehicle and I_1,$(\theta(t))$, will be a constant $(Q_o+\theta_o)$. This is assuming the vehicle



Note: The apparent contradiction in notation caused by using the subscript zero and the (t) to indicate a time function is to indicate that although the values may indeed assume "initial values" in the usual fashion, the process may be repeated frequently as improved position data is obtained.

figure (2) Longitude Conventions

doesn't move. If it does the new longitude in the old prime meridian system will be just $(Q_o+\theta_o)+\phi(t)$, where $\phi(t)$ is the vehicle longitude in the M-frame. In the inertial I-frame this becomes $\theta_o+\omega_{mars}t+\phi(t)$, where the term $\omega_{mars}t$ reflects the planet rotation in inertial space. Latitude measurements are not so arbitrary, as the spin axis of Mars is well defined in space and in fac may be observed by comparisons with stars, much as for the North Star on earth. There is a second magnitude star within 2 degrees of the Martian south pole [11], and a star pattern could be used for similar tracking of the north pole if required. Latitude is therefore measured in the conventional sense with the equator being zero degrees and the poles ninety.

6. VEHICLE FRAMES. The vehicle basically operates in a body-bound or B-frame mode. That is, when it wants to move it does so by directing its own physical structure in some given direction with respect to its present position - left, right, forward, backward, etc. Unfortunately, it is not easy to directly relate this B-frame to a geographic or inertial frame so that calculations can be made for navigation and guidance. Accordingly, the vehicle needs some intermediate reference frame which it can carry with it. This frame, called the x-frame, must be relatable to the space in which the satellite makes its calculations and observations - inertial, and it must be able to also relate to the direction over the ground along which the vehicle must travel - geographic. Of course, the frame is still of little use if it can't also relate all this information back to the original body frame. These requirements are not unique to this mission, and have given rise to the entire technology

of stable platforms. For purposes of this paper, however, a decision was made to attempt to avoid the conventional method of stabilizing and instrumenting this platform with gyros and accelerometers. This was primarily because accelerometers are ineffective for slow speeds and high vibrations, while gyros tend to drift. Instead of the accelerometers, a direct surface velocity sensor is used, and although a platform is still intended, it uses sensors continually aligned with stars, the sun, or local vertical for its reference. While this platform does not have the advantage of extensive technological development and does have certain geographic limitations, it has the advantage of being continuously self-correcting; i.e., no drift. This elminates the need for realignment, which becomes more important as time and the number of maneuvers increase. For a mission of several months this could actually represent a considerable decrease in complexity of operation, especially in mechanical functions. The major weakness of the system is that no one combination of reference vectors, (star, sun, local vertical), is applicable to all parts of the planet for all times of the year. This deficiency must be overcome by logic circuits designed to select the optimal combination for the conditions. Some examples follow.

A. Pole Star-Local Vertical Frame.

Once the vehicle has landed and basically righted itself, it must make two observations to establish this reference frame - local vertical, and the southern pole star of Mars. Local vertical (direction only) is established by use of the instrument described in Appendix I, which is basically an instrumented damped pendulum.

This device establishes one primary axis of the frame which is then related to the terrain model and stored. Observation of the southern pole star is more restrictive. The first obvious problem is that it can't be seen at all from above 25 degrees north latitude and only during certain parts of the year from 25 degrees north to 25 degrees south. Because of the very thin atmosphere, the star could probably be followed in the daytime on clear days, but any low-level turbulence or dust storms could cause trouble. The star would initially be recognized by photographing the entire sky and transmitting the pictures to earth for interpretation. Once acquired, the star can be followed continuously as Mars rotates because of its alignment with the rotational axis, and would only need to be re-acquired if lost because of atmospheric interference. The star is a second magnitude star within two degrees of the pole and is in an easily recognized cluster [11]. There is no north pole star for Mars, the nearest being Deneb, which is 10° from the axis. A first correction for the two-degree ambiguity could be made by knowing the vehicle's approximate longitude and the time. The tracking device would be a standard star-tracker currently in use for space navigation, and should be accurate to within less than +0.2 degrees [12]. The frame is generated by taking the cross product of the two observed unit vectors and then crossing the star axis with the result of the first operation. This system is geometrically good for exploration of the areas between about 10 degrees north and 60 degrees south (because of the large angle between local vertical and the star axis in these areas) and is computationally nearly ideal. The fact that one axis is parallel to the axis of rotation of Mars and that the other two axes form a plane parallel to the equatorial plane make the system very easy to relate to the Martian geographic frame. If the vehicle does not move, the frames remain permanently aligned, the vehicle reference frame rotating with the planet, and any vehicle motion can produce only one degree of rotation of the vehicle frame with respect to the Martian frame, and that is about the Martian axis of rotation; that is, a change of latitude will produce no rotation between the frames, and a change of longitude produces only a single component rotation. The transformation matrix is composed of terms which are only functions of one variable, longitude. Hence, if the selected area of exploration is in the mid-latitudes or tropics of the southern hemisphere, on relatively flat land, with a minimum of local dust storms this system could be easily instrumented, and would be computationally excellent. For the dead-reckoning scheme of section(8)[14] the same vectors are used but a local horizontal plane is formed instead of one parallel to the equator, which makes the computations even simpler.

B. Sun-Local Vertical Frame.

The restrictions on the vehicle frame mentioned above may be changed by using the sun instead of the pole star as a second reference vector. The sun has the disadvantage of passing out of sight each day and passing nearly overhead, (and therefore in line with local vertical), for all operations in middle and lower latitudes. This also implies that such a system would be geometrically ideal for use in summer exploration of the polar areas, where the sun never sets, and is almost always close to 90 degrees away from local vertical. The problems in the lower latitudes may not be as bad as they seem either,because although the sun sets each evening, it is easily re-acquired in the morning by its extreme brightness. A simple array of photocells would do for a coarse sensor, and a filtered telescope could track the sun accurately through almost any kind of dust storm. [15] The possibilities of singularities could also be reduced by careful selection of time and place of exploration. Since the rough calculations of Appendix II indicate that the frame maintains reasonable accuracy until the two reference vectors - the sun and local vertical - come within 25 to 30 degrees of each other, the area just south of the equator could be explored using this frame during the northern hemisphere's midsummer, and vice versa. At these times the sun is passing meridian transit at an angle from the zenith equal to 25 degrees plus the observers latitude [16]. Even with the proper choice of time and location, however, the sun frame has one definite disadvantage when compared to the pole star frame and that is the fact that the motion of the sun frame with respect to the Martian geographic frame is not a simple one. The fact that Mars both rotates on its axis and travels around the sun makes the plane of the local vertical-sun lines move at a difference rate each day and over each interval of time in a given day. Since this motion is also a function of vehicle latitude and longitude, the problem is very complex, and would require a data bank similar to an almanac. Even if such a bank were assembled, it would only be as good as the accuracy of the vehicle's latitude, longitude, and clock. If this motion could be reduced to a useable equation, perhaps linearized, it might be possible to have the vehicle do its own solution instead of carrying a large memory. If the problems of relating the sun frame to the Martian geographic frame can be solved, the sun frame would represent a significant improvement in ease of instrumentation over the pole star system.

7. THE SATELLITE-UPDATE SYSTEM. It was mentioned in the introductory discussion that one of the primary capabilities of the system is to be recognition and location of various surface targets for the vehicle's exploration. This is to be accomplished solely through the use of the orbiting satellite. The system involves having the satellite measure two vectors and then solve for their vector sum. Specifically, the satellite must measure its position in the I-frame and the vector from the satellite to the target, again in the I-frame. It then uses these to compute the geographic position vector of the target itself, (r,λ,ϕ). The same principles are involved in the second phase of the process which involves the determination of a similar set of coordinates for the vehicle - r,λ, and ϕ. In this instance however, the vehicle is much too small to be found optically by the satellite, so the satellite simply transmits its position in orbit (I-frame), to the vehicle, which then observes the satellite and solves the triangle for its own position. A disucssion of the errors involved in this system will be deferred until later. Instead, a few of the special problems of instrumentation will now be covered followed by a discussion of the implications of the natural restrictions of the vertical look-angle capabilities of the vehicle on satellite orbit choice.

A. Instrumentation.

The satellite's portion of the observations present some problems which are quite different from those of the vehicle. The satellite has an easily maintained inertial frame because the satellite body itself is nearly inertial, and can have its aspect maintained by normal star checks. Establishing the reference frame is therefore the easy part. The hard part is first locating and then tracking local vertical and the landmark. Because of the orbital velocity of the satellite and the resulting centrifugal force, the actual force of gravity is not available to allow use of a simple pendulum sensor, only the gradient. This is a problem because the anomalies in Mars' shape and mass distribution produce variations in the gradient which can set up oscillations in any gravity-gradient oriented body, as indicated by the irregularities in the orbits and rotations of Mars natural satellites.[17] The possibility of optical bisection of the planet is somewhat promising because at the altitudes involved (400-800 miles) as the satellite passes over head the horizons subtend an angle of only about 90°. The actual scheme used determines the orbit of the satellite accurately by celestial observations and then computes local vertical as a function of time for each pass, local vertical being the direction of the focus of the ellipse which is at Mars' geocenter. If position of the satellite in the orbit is known, the direction of the vector can be compared with optical bisection data. Unfortunately, there is no apparent computational way around the next problem which is tracking the landmark. A possible solution is to utilize earth-based facilities to provide the satellite with directions on what the target looks like and where to find it each time a new target is desired. Since the landmark image is going to be a function of both lighting, (time of day, time of year, atmospheric conditions) and satellite position, the control facility on earth would have to model the situation as closely as possible for each first encounter and send the satellite a prediction on what sort of pattern to look for, and where in the satellite's reference frame to find it. Both of these are made difficult primarily because of the limited knowledge of the Martian terrain details. The camera in the satellite doing the tracking is likely to see a lot of things which can't be predicted from earth and possibly the other way around because of the camera's limited field of view. It may well be that such a system would have to use a fairly wide-angle, low resolution camera to simulate the earthbound view of things, and then track the optical center of some fairly large target. Although transmission delay time of several minutes precludes having earth actually verify target acquisition each time, a few practice runs might be made either on preceeding missions or on the first few passes of the actual mission, or both. The details on this system are still not satisfactorially resolved.

B. <u>Available Planet Coverage for a Given Look-Angle and Orbit</u>.

For purposes of calculations, planet parameters will be as follows:[18]

equatorial radius	=	3388 km $\pm$ 50 km
polar radius	=	3334 km $\pm$ 68 km
average radius	=	3361 km $\pm$ 60 km
	=	2090 miles $\pm$ 37 miles (1.8%)
g mars	=	.38 g earth = 12.2 ft/sec^2
T mars	=	24 hr. 37 min $\approx$ 24.5 hr.

The period of orbit (T) of the satellite may be computed for a circular orbit for any altitude (a) as follows:

$$g\ mars = \omega^2 (a + R\ mars)$$

$$\omega = \sqrt{\frac{g\ mars}{(a+R)}}$$

$$T = \frac{2\pi}{12.2}\sqrt{a + 2090}$$

Now in figure (2) it may be seen that for any given period of time T, a point on the equator moves a distance $y = \frac{2\pi(2090)}{24.5}$ T, which is an angular displacement of $\frac{2\pi(57.3)}{24.5}$ T = w(degrees).

The equator is chosen because the surface there moves the largest actual distance in a given period of time. In figure (2) the vehicle (V) is shown on the edge of a swath of width Y such that if the vehicle has a look angle α it will just see the satellite on this pass; any smaller α and the vehicle could miss the satellite altogether, but a slight increase could allow sightings on two consecutive passes if the satellite passes exactly Y/2 miles from V on the first pass. If the actual planet rotation during the period of circular orbits at various altitudes is calculated, the required look-angle α for a vehicle on the edge of the swath may be found by the law of sines, or graphically as shown in figure (2). For a = 800 miles, T = 1.95 hr. planet movement = 28.7°, (1005 miles at the equator), W/2 = 14.3°, and the necessary look-angle α is found to be 45°.

Other situations are as follows:

a	T	W/2	α
200 mi.	1.74 hr.	12.8°	23°
400 "	1.80 "	13.4°	60°
500 "	1.84 "	13.6°	54°
700 "	1.92 "	14.1°	47°

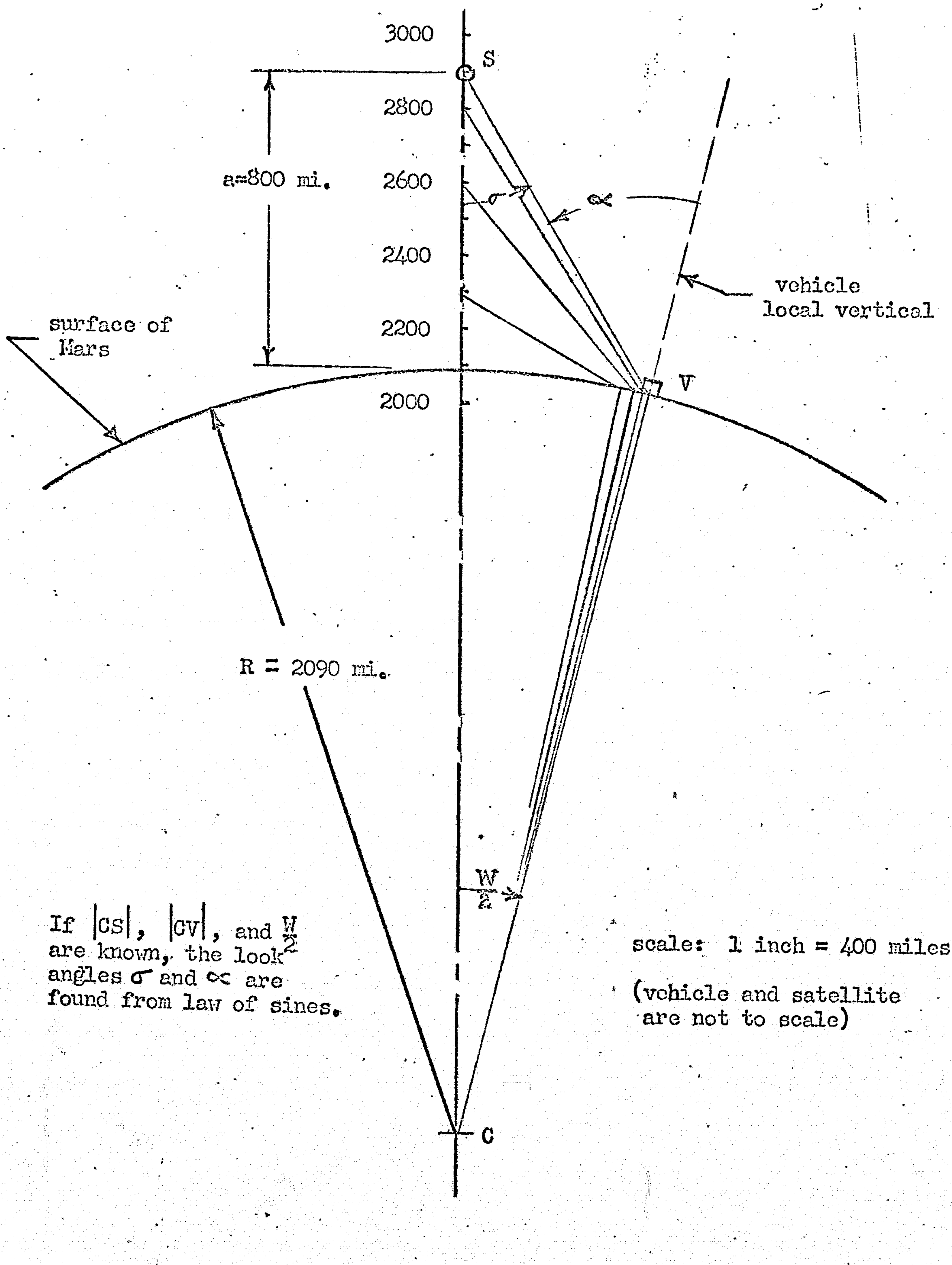


figure (3) Look Angle Analysis

800 mi.	1.95 hr.	14.35°	45°
900 "	1.98 "	14.75°	43°

This all implies that to insure coverage of all points on the equator at least once per day in a polar orbit, (twice per day if circular or at least nearly enough so that satellite never passes out of sight because of excessive altitude). Such orbit of course, covers all other points on Mars at least twice a day, and covers all points within W/2 degrees of the poles on every orbit. This is also assuming no vehicle movement between orbits. This assumption is not really bad because a movement of 2-3 mph for 2 hrs. is only 5 miles, which can only be a problem if the vehicle is exactly at boundary of passes and no overlap is built in. This orbit can be inclined W°/2 from pole and still cover everything, plus provide an extra 4 miles width per pass at equator ($Y_{new} = Y_{polar} \cos\frac{W}{2}$). Of course, if the poles are not to be covered, (a) can be lowered and points near the equator covered easily several times a day with an orbit a few degrees off the equator.

The main result of this study is that for full global coverage (a) must be 400-800 miles as α goes from 60° down to 45°. This increased altitude will mean more time overhead, slower tracking rates, better general viewing angles of targets and possible horizon-to-horizon angle measurements for navigational use, local vertical checks, etc. (Horizon-to-horizon is about 97° at 800 mi.) Note that 400-800 miles is also an easier, safer orbit, being well out of tropopause. Bad points are loss of resolution of landmarks and increased communications power requirements.

C. Time Overhead

For $\alpha=45°$, $a=800$ mi., the satellite will be in view a maximum of W degrees of its orbit as shown (this is best case-satellite passes overhead). $W=28.7 \approx \frac{1}{2}$ rad, so distance $S_1S_2 = \frac{R+a}{2} = \frac{2890}{2}$mi. Now time overhead = $t_{oh} = \frac{S_1S_2}{V} = \frac{2890/2}{\omega 2890} = \frac{I}{4\pi}\,\frac{(60\text{ min})}{\text{hr.}}$ = 9.3 minutes maximum, (0.0+min.) For $\alpha=60°$, $a=400$ mi., $W=26.7°$ = .466 rad, t_{oh} = 8.05 minutes (max)

Note that there would have to be some overlapping of coverage to insure at least 1-2 minutes in the useable field of view.

8. DEAD RECKONING. It should be noted that the satellite update system derives much of its value from the ability to take several readings on the target or satellite and then improve the data by stochastic fitting. This of course requires a good prediction for the next set of data points. For a fixed target this is not too difficult because each solution can use the previous one as an estimate and eventually converge on a true solution. For the vehicle, however, a better system is needed. Accordingly, the development of a system to measure vehicle movement on the surface with respect to some arbitrary starting point has been considered. Previous work by Mr. Hedge [13] and Mr. Chen [3] established a basic scheme for integrating surface velocity, but the scheme was dependent on the ability to measure surface velocity directly in the vehicle V-frame. Since no sensor was found which could do this, a new version of basic terrain roughness sensors [19] was devised by the author to accomplish this task by sensing vehicle velocity over the surface in both the vehicle lateral and longitudinal directions and then translating to the X-frame.

A. <u>Surface Velocity Sensor</u>. In order to measure surface velocity of the vehicle in the body frame, the following modifications to the basic castored wheel and arm used to balance the R.P.I. vehicle in the tilt-back mode are proposed.[20] Note that the objectives of the device are to measure two vectors--vehicle velocity in the fore-and-aft direction, (V_{B_1}), and vehicle velocity in the athwartships or side-to-side direction, (V_{B_2}). The first is the desired or ordered velocity, and the second is caused by the vehicle sliding sideways, as on the side of a sand dune. The lateral movement sideways is not to be confused with slippage of the tires individually, as in a turn, (release). It will be shown that under reasonable assumptions concerning the steering ability of the vehicle, it is possible to separate these two by using information from the vehicle reference frame (V frame) and the position of the steering wheels. Since these calculations help clarify the function of the new version of the trailing arm, they will be given before the details of the modifications to the arm are explained.

(1) <u>Interpretation of Arm Position Data</u>.(see figures 4,5,and 6).

The basic data available from this arm are the wheel rpm, (Ω_W), arm horizontal deflection, (ϕ), and arm vertical deflection, (ξ). The wheel rpm can be converted directly to a velocity by multiplying by the wheel radius, giving a velocity reading from the wheel (V_W), which must be converted into the two components, $V_{W(B_1)}$ and $V_{W(B_2)}$.

The equations for conversion are as follows:

$$V_{W(B_1)} = V_W \cos \phi$$
$$V_{W(B_2)} = V_W \sin \phi$$

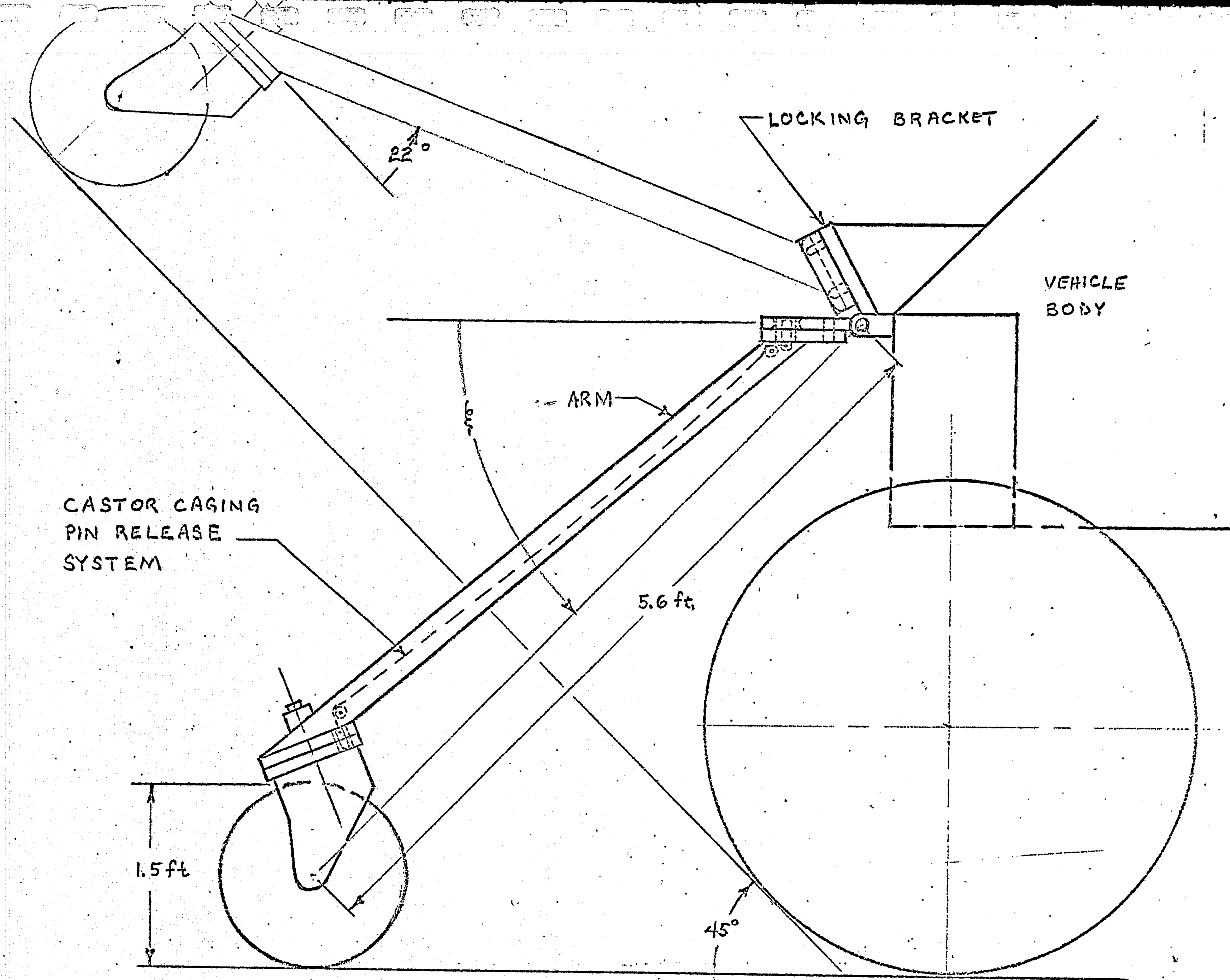


figure (4) Surface Velocity Sensor

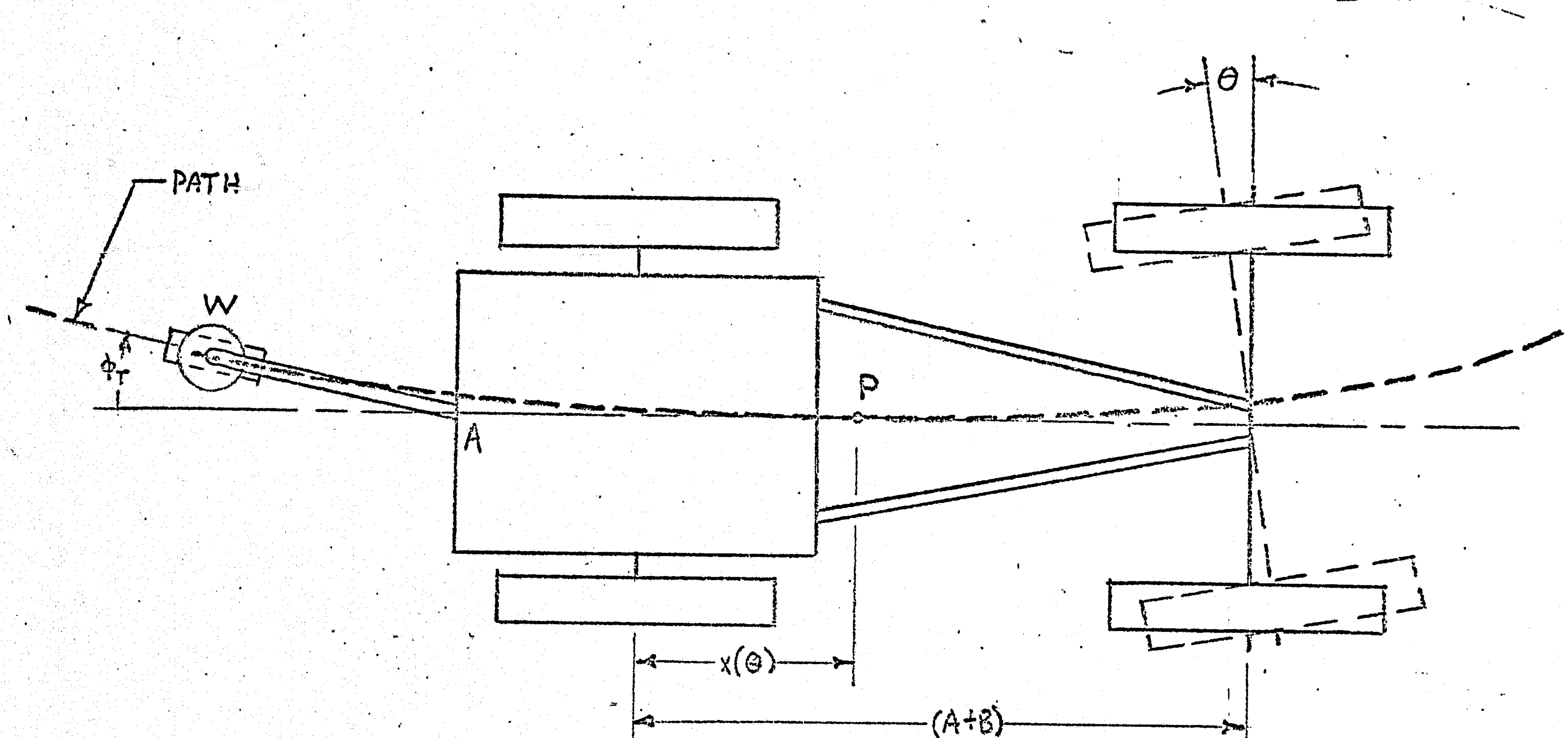


figure 9(5) Arm Deflection in a Turn

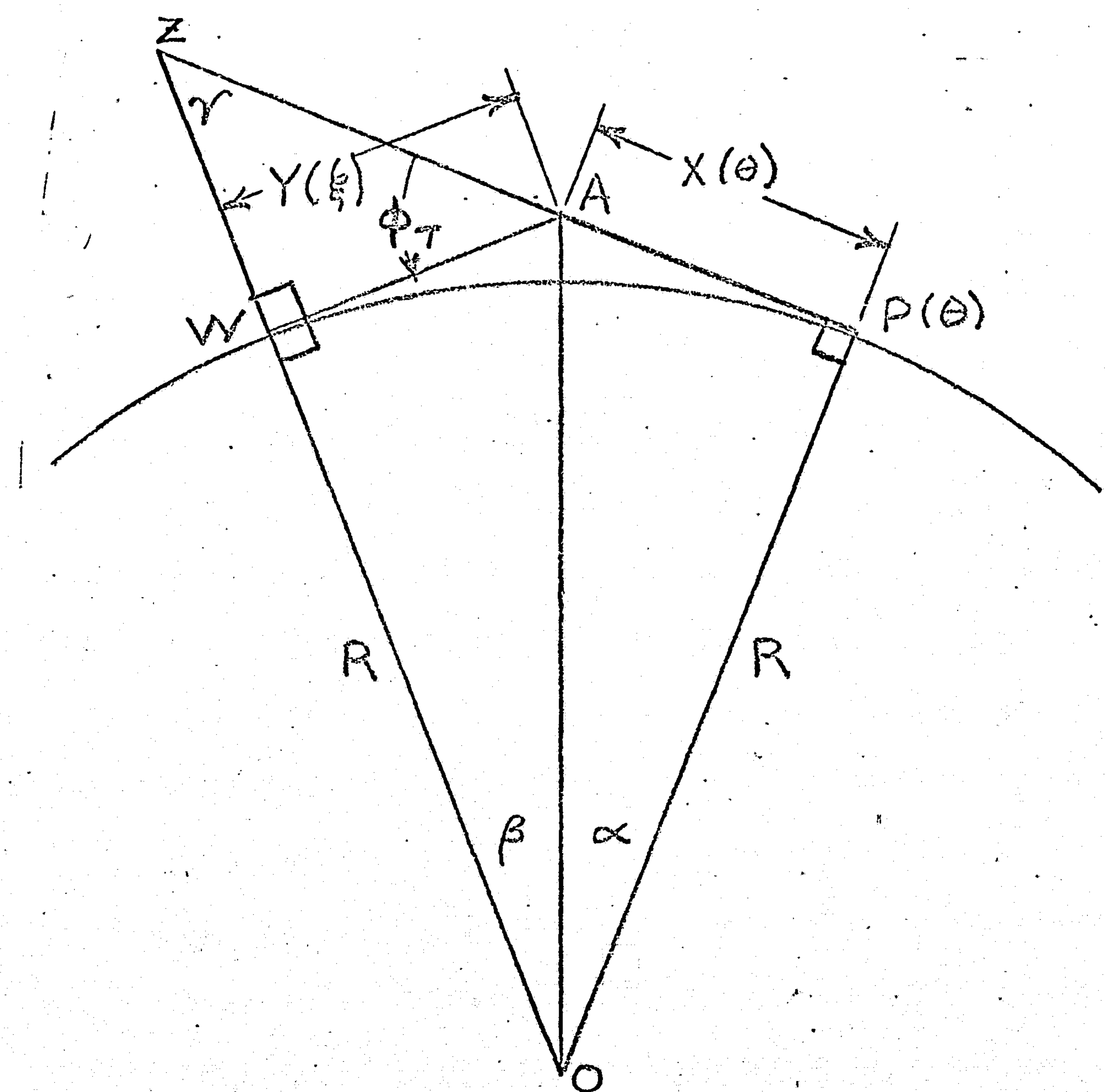


figure (6) Calculation of ϕ_T

The conversion of the two perpendicular components V_{wB_1} and V_{wB_2} into the actual vehicle forward and transverse velocities is easy if the vehicle is not turning; that is, the vehicle is keeping its bow pointed in a constant direction with respect to the surface but is perhaps translating laterally (by sliding). In this case, assuming the sensor wheel doesn't slide (because of a very rough tread and light weight), the readings give

$$V_{w(B_1)} = V_{B_1}$$

$$V_{w(B_2)} = V_{B_2}$$

In other words $$\frac{V_{B_2}}{V_{B_1}} = \text{TAN } \phi$$

It should also be observed, however, that a normal turning motion of the vehicle will also produce an angle ϕ_T at the trailing arm as the sensor wheel "follows" the vehicle around the turn. This angle may be predicted for any given steering angle of the front wheels θ as follows:

Under assumptions of negligible front wheel steering skid, (because of large size and slow speeds), the Akerman angle θ is proportional to wheel base, (A+B), and inversely proportional to the radius of the turn (R),[21]

$$\theta = \frac{57.3(A+B)}{R}$$

so $$R = \frac{[57.3(A+B)]}{\theta}, \quad (A+B \simeq 10 \text{ ft})$$

$$R \simeq \frac{573}{\theta}$$

where it should be noted that for this vehicle, the wheel base is a variable. For a given computed R, the angle ϕ_T may be found as follows:

O = Center of turn

$P(\theta)$ = Turning point of vehicle

A = Arm Attachment Point

W = Sensor Wheel

$x(\theta)$ = Distance from $R(\theta)$ to A

$y(\xi)$ = Horizontal projection of Arm on the ground (5.6 cos ξft.) = $y(\xi)$

z = Vertex of Triangle used in calculations

ϕ_T = Horizontal Deflection of Arm caused by turn

Note that $P(\theta)$ varies from the midpoint of the wheelbase to directly over the rear wheels as the turn angle θ varies from 0 to 90 degrees and would need to be determined empirically.

Now,
$$\frac{x(\theta)}{R} = \text{TAN } \alpha$$
$$\frac{y(\xi)}{R} = \text{TAN } \beta$$

in triangle OPZ,
$$(\alpha+\beta) = 90° - \gamma$$

in triangle AWZ
$$\phi_T = 90° - \gamma$$
$$\therefore \quad \phi_T = \text{TAN}^{-1}\left(\frac{x(\theta)}{R}\right) + \text{TAN}^{-1}\left(\frac{y(\xi)}{R}\right)$$

Now the final conversion can be made, giving
$$V_{B_1} = V_W \cos(\phi - \phi_T) \qquad (1)$$
$$V_{B_2} = V_W \sin(\phi - \phi_T) \qquad (2)$$

where ϕ_T is defined as above

Some examples follow: For small θ, say 10°, $x(\theta) \simeq \frac{1}{2}(A+B) \simeq 5$ ft., and with $\cos\xi = .707$ (level ground),
$$R = \frac{573}{10} = 57.3 \text{ ft.}$$
and
$$\phi_T = \text{TAN}^{-}\left(\frac{5}{57.3}\right) + \text{TAN}^{-}\left(\frac{3.9}{57.3}\right)$$
$$= 5° + 3.9°$$
$$\phi_T = 8.9°$$

For $\theta = 30°$, taking $x(\theta) = .3(A+B) \approx 3$ ft. and again on level ground

$$R = 19.1 \text{ ft.}$$

and

$$\phi_T = TAN^{-1}\left(\frac{3}{19.1}\right) + TAN^{-1}\left(\frac{3.9}{19.1}\right)$$

$$= 8.9° + 11.6°$$

$$\phi_T = 20.5°$$

If the vehicle were to transverse a steep side slope and slide laterally down at say one half foot per second while moving ahead at two miles per hour, (2.9 fps.)

$$\phi = TAN^{-1}\left(\frac{.5}{2.9}\right) = 9.8°$$

Of course, if the vehicle slid with no forward motion $\phi \to 90°$, just as $\phi_T \to 90°$ as $\theta \to 90°$ when turning.

Of course, this model of the computations would need more elaboration to handle the case of a vehicle which didn't slide sideways uniformly; that is, when the rear releases first, causing a rotation of the vehicle as it slides down the hill. This rotation would be sensed by the vehicle reference frame which would then check the guidance systems to see if the turn was intentional or a slide. If a slide, the wheels would be turned in an "oversteer" to keep the vehicle's head in the right direction until the slide stopped, since this would likely produce a smaller total position error than allowing a large unintentional swing of the vehicle's head. This would also produce a more accurate measurement of the error, which is what really counts except in very tight situations. A more sophisticated propulsion system might also be able to steer a given course in the presence of slide much as an aircraft holds its course by weathercocking into a cross-wind.

(2) Construction Details. (see figures 4 and 7)

The sensor consists of a castored wheel about 18" in diameter at the end of a rigid tubular arm about 5.6 feet long. The wheel is to be about 4"-6" wide with a rough tread to provide a good footprint for support of the vehicle in the tilt back mode and minimize slippage in the sensor mode. The wheel would have to be nearly rigid and strong enough to support the vehicle but light enough to minimize side-slip on cross-path slopes. A spoked construction with a wide tread-patterned metal rim would probably do. The wheel is free to castor when the vehicle is tilted back, but is pin-locked in line with the arm when acting as a sensor, (details later). The arm is connected to the vehicle by a two-degree-of-freedom hinge as shown in the detail sketch. This hinge is instrumented to read the angles ξ and ϕ of the preceeding derivations. Needs for spring or viscous damping of the hinge may be determined by analysis of resonant frequencies of the design once materials are chosen and more details of the terrain model become available. The system also uses a locking bracket which cages the arm in the fore-and-aft alignment when the vehicle tilts back. This bracket also depresses a pin which, by means of a cable, releases the caging pin in the wheel castor bearing, allowing the wheel to function as a castored support for the vehicle as it moves or rotates in the tilted position. Once the vehicle tilts forward, the arm moves free of the locking bracket. As the vehicle moves forward, the wheel castors to a trailing position in line with the arm and is locked there by the spring-loaded castor bearing caging pin. On level ground the wheel will be a nominal depression angle ξ of

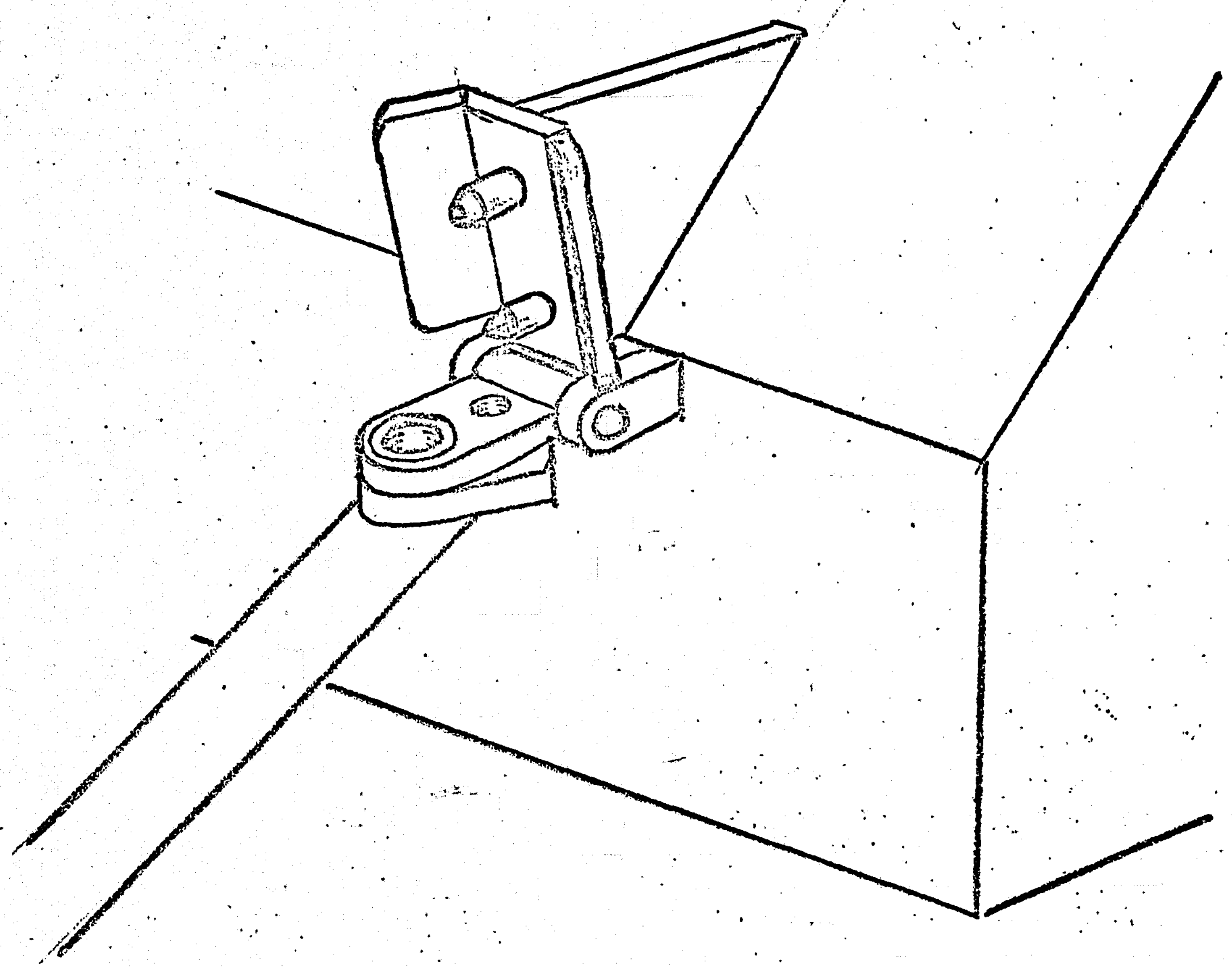


figure (7) Detail of Hinge and Locking Bracket

45°, with a maximum of 90° should the vehicle pass over a hole more than 1.8 feet deeper below the arm then below the rear wheels and a minimum of -20° when the arm is caged in the locking bracket. Full swing left and right is plus or minus 90° up to $\xi = 0°$, which is when the caging arms of the locking bracket begin to engage.

The main effects of this modification on the rest of the vehicle are a slight lowering of CG because of the arm trailing on the ground instead of being suspended; a slight weight increase because of the lengthened arm, (+2.6 ft.), and hinge/bracket/instrument addition; improved stability in the tilted mode because of the lengthened arm, providing a wider base and less rocking as the castored wheel moves over obstacles.

9. MERIDIAN TRANSIT. On earth one of the oldest and most widely used celestial observations for surface navigation is the time and altitude of the meridian transit of the sun; that is, the point each day when the sun passes due south or north of the observer and reaches its maximum altitude. This is now used primarily because of the simplicity of the calculations required to obtain a direct, accurate line of latitude. It is proposed to use a similar observation from the vehicle on the surface of Mars to obtain both latitude and longitude. The actual measurements required are the angle between the local vertical vector and the sun and the time at which the sun reaches its maximum altitude - which is when the measured angle α reaches its minimum. If the sun-local vertical system is being used as a reference frame for navigation, this measurement will already be instrumented, and require only the addition of a triggering device to sense when the measured angle

reaches its minimum and starts to increase. The device simply records the angle and the time and sends this data to earth for interpretation.

With the time known, the angle of inclination of Mars' axis to the plane of its orbit can be calculated and with some possible estimates for refraction, semi-diameter of the sun, and other standard sighting corrections the latitude can be computed by combining the observed angle and computed axis inclination as in figure (8). Since the observed angle can in general be read from two different latitudes, this singularity would have to be resolved by outside sources. For a sun-local vertical frame however, this angle must be kept fairly large from the frame to remain accurate, so the resolution of the singularity should be quite easy. The longitude is computed by noting the time of the observation and then computing what meridian of longitude on Mars should have been facing the sun at that time. This requires a knowledge of Mars' and Earths' positions in orbit and the Martian meridian facing Earth at the time of observation. As shown in figure (9), the longitude of the vehicle equals the longitude of the meridian facing Earth plus the angle τ, (as calculated from the position of the two planets in orbit).

An observation of meridian transit on earth gives latitude within about one mile,[22] but this is in a statistically known atmosphere with complete tables and many years' experience and refinement. The Martian measurement error from atmospheric uncertainty and instrument error should probably be no more than five time as large, and since the error is angular, converting a one mile error

i = inclination
α = observed angle

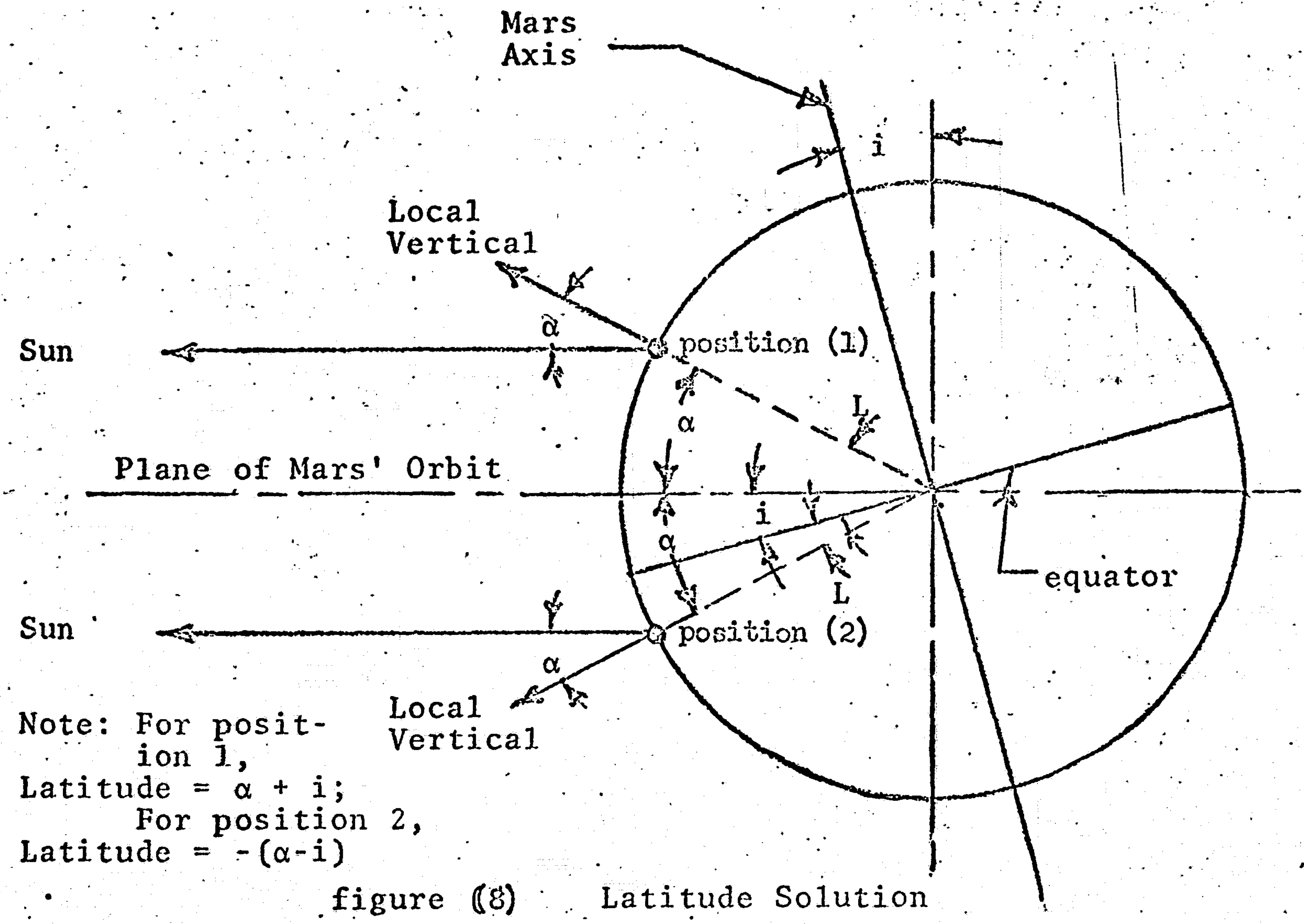


figure (8) Latitude Solution

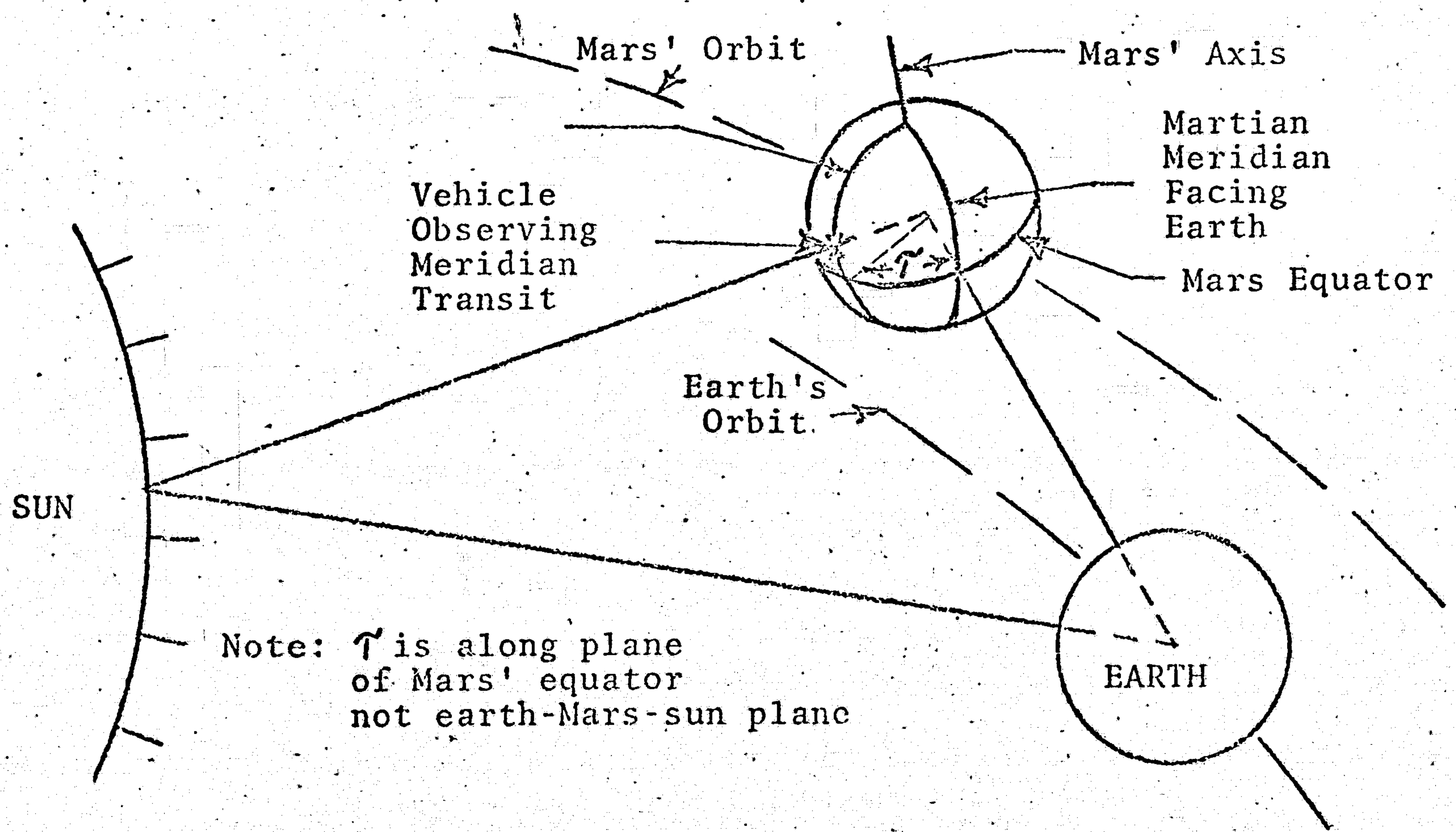
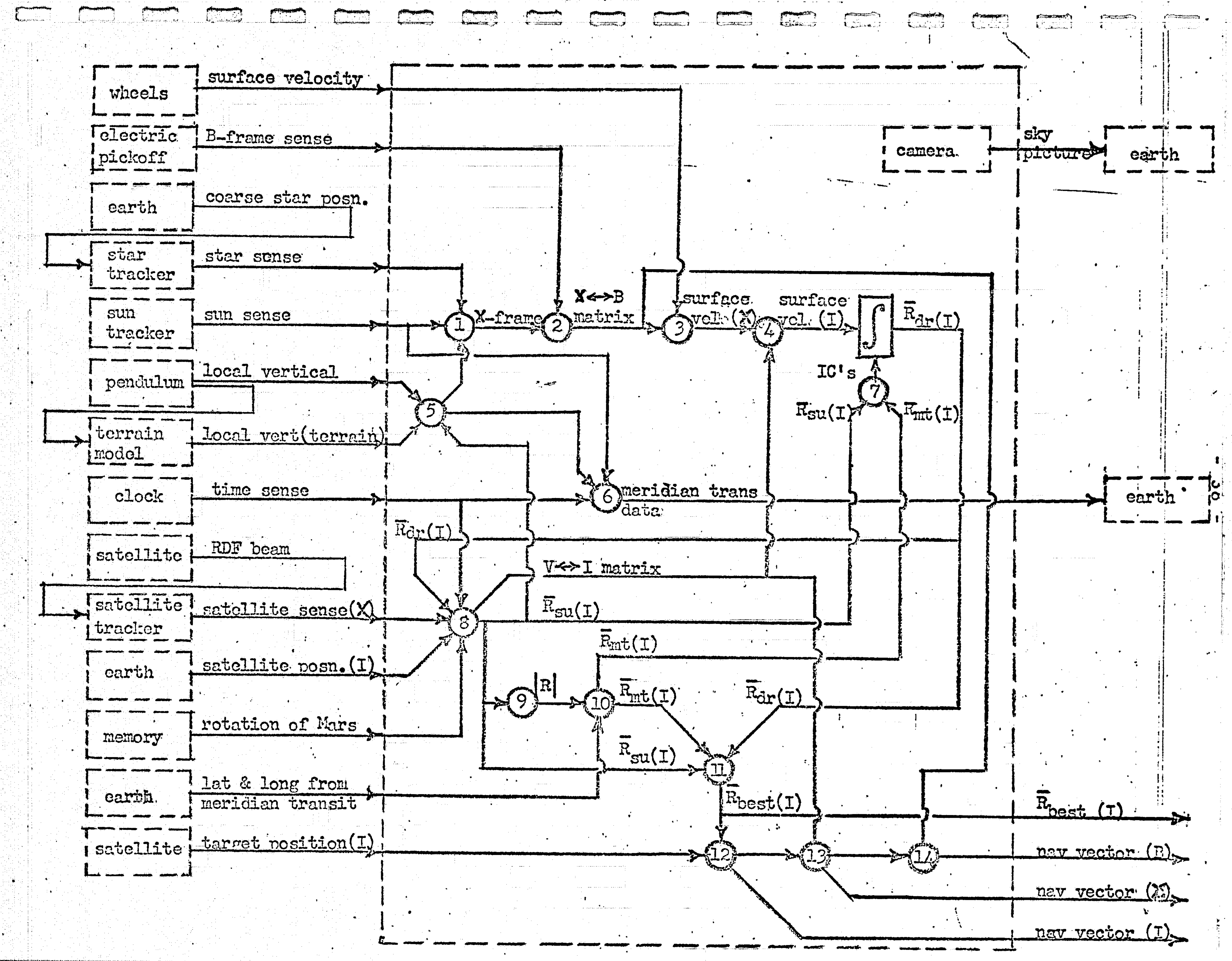


figure (9) Longitude Solution

on earth to an angular error, multiplying by five and reconverting to distance using the reduced Martian radius gives a position error of about 4 kilometers. Since the position of the Martian prime meridian is only established within about 60 kilometers,[23] the sighting accuracy is well within the accuracy of the grid system presently available. The value of 4 kilometers could also probably be reduced as data on the atmosphere becomes available and as, or if, the vehicle spends more than one day in the same spot so it can repeat the measurement. Also note that time is a factor here. An error of four full seconds produces a one kilometer error. If the vehicle clock were corrected from earth once each day before the observation, however, this error could become negligible and significantly improve the accuracy.

10. BLOCK DIAGRAM. To summarize the relationship between the basic techniques of sections 7 thru 9 a block diagram of the proposed arrangement of the primary navigation system is shown in figure (10), The inputs are shown on the left, where the sensors and other sources are considered to be a part of the system. The outputs on the right are sent to the guidance section for use by the algorithm in guiding the vehicle along the optimum path. Note that the output may be in one of two basic forms - either a statement of the vehicle present position ($\overline{R}$ best), or the navigation vector itself in any of three frames, depending on which the algorithm finds most convenient. The other "outputs" on the right are not strictly outputs because they are transmitted from the vehicle to earth for processing and return, where earth is considered a part of the overall navigation system for certain operations. Note also that the numbered circular junction symbols used in the diagram



wheels
surface velocity
electric pickoff
B-frame sense
earth
coarse star posn.
star tracker
star sense
sun tracker
sun sense
pendulum
local vertical
terrain model
local vert(terrain)
clock
time sense
satellite
RDF beam
satellite tracker
satellite sense(X)
earth
satellite posn.(I)
memory
rotation of Mars
earth
lat & long from meridian transit
satellite
target position(I)
X-frame
X<->B matrix
surface vel. (X)
surface vel. (I)
$\bar{R}_{dr}(I)$
IC's
$\bar{R}_{su}(I)$
$\bar{R}_{mt}(I)$
meridian trans data
$\bar{R}_{dr}(I)$
V<->I matrix
$\bar{R}_{su}(I)$
$\bar{R}_{mt}(I)$
|R|
$\bar{R}_{mt}(I)$
$\bar{R}_{dr}(I)$
$\bar{R}_{su}(I)$
$\bar{R}_{best}(I)$
$\bar{R}_{best}$ (I)
nav vector (R)
nav vector (X)
nav vector (I)
camera
sky picture
earth
earth

are not the conventional summing junctions of control systems diagrams, but rather represent various kinds of comparative and manipulative operations. In face, it is the analysis and design of these specific operations that comprises the bulk of the detailed work of the project. The numbering system is for ease of location on the diagram rather than precise tracing of information flow. The diagram is constructed as follows:

A. Establishment of Vehicle Reference Frame.

This process combines sun, star, and local vertical inputs to produce the X-frame. Junction 5 combines the various measurements of local vertical, (including the use of a pendulum when the vehicle is stopped, tracking of nearby terrain features when moving, and an occasional check by comparison with satellite sighting data), to pass the best available value of local vertical to junction 1. At this point, local vertical is combined with the vectors to the pole star and sun. The two which are appropriate to the situation are then chosen and cross-products are taken to form the X-frame as discussed in previous reports. An example of this decision process would be a choice of the sun and pole star for summer exploration at the south pole during either day or night, or a choice of local vertical and the sun for exploration of northern mid-latitudes during daylight.

B. Meridian Transit.

A combination of the sun position, local vertical, and time at junction 6 gives a set of data which is transmitted to earth for interpretation and return as a latitude and longitude of the vehicle at local apparent noon on the day of observation.

C. Dead Reckoning.

Dead reckoning is the practice of estimating a position by taking the integral of ordered course and speed from some given initial position. [24] In this case, the "ordered-course-and-speed" approach is improved on by actually measuring vehicle velocity with respect to the Martian surface, transforming from the body frame (B-frame) to the inertial frame, (I-frame), via junctions 3 and 4 and integrating to obtain an estimate of vehicle position $\overline{R}_{dr}$. The initial conditions for the integration are taken from junction 7 as the best or most recent of the satellite-updated position and the meridian transit position.

D. Satellite Update System.

Junction 8 is by far the most complex of the system. At this point the basic computation is made for vehicle position by combining the satellite observed position relative to the vehicle, its computed position relative to the center of the planet and an estimate of the vehicle's position. Through a fitting process the vehicle position is computed and the transition matrix between the V-frame and the inertial I-frame is established.

E. Computation of Outputs.

The basic comparison and weighting of the three position estimates, $\overline{R}_{dr}$, $\overline{R}_{mt}$, and $\overline{R}_{su}$ is made at junction 11, (the magnitude of $\overline{R}_{su}$ is combined with the earth input of meri dian transit latitude and longitude at junction 10 to form $\overline{R}_{mt}$). $\overline{R}$-best is then fed directly out, and also used at junction 12 in combination with the computed target position from the satellite to form the naviation vector. Note that the main central block within the dashed line may be viewed as the primary navigation section of the main vehicle computer.[26]

F. Communications Links.

The system may also be summarized from another viewpoint by tracing the various communications links which are necessary for the functioning of the major components - the vehicle, the satellite, and the earth. Figure (11) shows these links. It may be noted that most of the links are rather conventional S-band or UHF radio telemetry, but since the messages sent are of widely varying types it may well be that special new types of coding will have to be developed to allow the system to handle the large variety of messages. For instance, if the pictures which are transmitted back to earth for analysis in finding targets, locating stars, or resolving an impasse in the terrain, the data must be easily filtered so that decisions can be made in a short time without the benefit of the many months of computer enhancement that is now applied to such pictures. Such a system may be far more complex than necessary for such items as a time check or a single data point on meridian transit, so that the communications system will have to be capable of allocating each message to the simplest and most efficient piece of hardware for the application involved.

Communications Links

Vehicle		Satellite		Earth
		o	star sights, planet dia, etc.	
		o	orbit data by unknown landmark	
x	satellite position (I-frame)	x,r	orbit data (best)	o
		x	orbit correction orders	o
x	RDF signal to confirm posn	o		
o	meridian transit data	r	meridian transit data	x
x	estimate of vehicle lat. and long.	x,r	estimate of vehicle lat. and lon	o
x	time checks	x,r	time checks	o
		x	ordered target, (picture &posn)	o
		o	target picture for confirmation	x
x	target computed position (I)	o	target computed position (I)	x
o	sky picture for star search	r	sky picture for star search	x
x	star location	r	star location	o
o	impasse data	r	impasse data	x
x	vehicle orders	r	vehicle orders	o
o	science observations	r	science observations	x
		o	science observations	x

note: o = originate
x = terminate
r = relay

figure (11) Communication Links

G. Hardware.

The basic hardware required for this system may be summarized as follows:

Vehicle Sensors	Vehicle Communications	Vehicle Computations
facsimile camera(find stars)	UHF data link to satellite	establish vehicle reference frame (X-frame)
star tracker	S-band for direct earth link for use in casualty modes or to increase available transmission time.	
sun tracker		
local vertical sensor		
radio directionfinder (to coarse sense satellite)		compute own position from observation of satellite.
laser tracker (track satellite)		
clock	————————————	integrate own velocity for DR estimate of own position.
surface velocity sensor		
		store previous best positions MT data, logic programs, and all sighting data from one transmission to earth to another (maximum 12 hrs.)

Note: If a gyro platform or body-bound gyros are used for the X-frame, the local vertical sensor may be omitted, and the star tracker would only be necessary if it was desired to make observations in the usual fashion for celestial navigation.

Satellite Sensors	Satellite Communications	Satellite Computations
star trackers (3)	UHF data link to vehicle	maintain own inertial attitude
landmark tracker (either optical image tracker or laser tracker for radiating beacons)	S-band direct to earth (handles own observations and relays for vehicle)	determine orbit by celestial observations and unknown landmark scheme
		find target and compute target position

Note: UHF links would not require directional antennas, both because of short range and because of high angular tracking rates. S-band antennas would require pointing systems.

11. ERROR ANALYSIS. Initial investigation into the actual hardware currently available to accomplish the tasks above indicated that there was a distinct shortage of available material on the subject. That is, equipment which is at or near state-of-the art just isn't listed in handy electronics catalogs, especially that developed for space applications. Accordingly, most of the initial numbers used in running sample problems on the various types of error analyses done are strictly guesses, and are quite rough. In general the numbers used are considered to be accurate only to within an order of magnitude. The references used on the accuracy of navigational sensors and systems come largely from earth-based equipment and so may be overly optimistic. The data on communications comes from the Project Viking work. In view of this situation, a detailed breakdown of the various sources of error is currently in progress by other members of the design team, so that a study may be made of the influence of each parameter on the total system. This work, (being carried on by Mr. Janosko), will serve to approach the problem from the other direction; that is, instead of designing a system which uses the present equipment it will determine what sort of accuracies are required of the sensors to properly implement the system as presently designed. The first estimates being used as starting values for the perturbations are as listed below:

A. For the dead-reckoning system:

(1) Initial position error - assumed one mile (spherical). This is based on the premise that considerable effort will be expended on determining the exact

position of the landing site before moving on, including several satellite updates, entry trajectory analysis, meridian transit observations, radio ranging by the Deep Space Network, and possibly a few star sights.

(2) Surface velocity sensor errors - assumed a proportional error of 2.0%, in magnitude with accuracy resolution on the angular measurement of 1°. Zero bias error is assumed.

(3) Clock error is taken as 2 seconds.

(4) Star tracker error is assumed to be 0.2°(also sun tracker).[12]

(5) Local vertical sensor accuracy is 2 seconds of arc when the vehicle is stopped but about one degree or more when moving. This makes the basic X-frame accurate to no better than 1.5 degrees when the vehicle is moving.

(6) Facsimile camera resolution to be as on Viking, (.04°)[26]

(7) Integration and computational equipment errors are assumed zero.

B. For the satellite update system:

(1) Satellite star trackers are assumed accurate within 2 seconds of arc.[12]

(2) The satellite reference frame is assumed accurate within 1 minute of arc.[12]

(3) Satellite position in orbit is considered known within 10 miles.[8]

(4) The laser tracker for the satellite from the vehicle is accurate to about 0.2 degrees, so the total angular position error of the satellite sighting is about 2 degrees. The error in satellite range is very small and nearly independent of the geometry of the situation. For the initial RDF acquisition system the range error is assumed 15 yards and for the laser system 15 feet.[26] The RDF system has an angular resolution of 3 degrees.

(5) The satellite can track a radiating target to the same accuracy as item (4). For a non-radiating landmark the accuracy is taken as the same as a low grade star tracker, 15 minutes of arc.

(6) Clock error is again taken to be 2 seconds.

Initial runs using the above estimates give an error of 24 miles in vehicle position as fixed by the satellite-update system, (without filtering), where most of the error was attributable to the error in sighting angle, (a combination of local vertical errors and tracking errors). Reduction of the local vertical error to the nominal value for a stationary vehicle reduces this error by half, and filtering could be expected to also improve the error a similar amount so that accuracy would be in the range of 2-5 miles. The analysis of the dead reckoning system shows that for a ten-hour period the dead reckoning accumulated errors are generally less than the total initial error of one mile. (The total distance travelled is thirty miles.)

<u>12. CONCLUSIONS</u>. The objective of this paper has been to explore the basic instrumentation of the primary navigation system. The results have included considerable re-design and organization of a proposal of that system. In summary, the system strong points are as follows:

A. The basic satellite update scheme is computationally strong, and provides considerable additional information to the vehicle which it cannot obtain from the surface. It requires only one additional tracker beyond the satellite's normal navigation package.

B. The vehicle dead-reckoning scheme also appears attractive because the relatively simple surface velocity sensor can give quite accurate relative position data. This is highly compatable with the satellite scheme, which needs good information to facilitate parameter estimation for fitting.

C. The meridian transit scheme is strong in its independence of other systems and ease of instrumentation.

The weak points of the system are as follows:

A. The use of a satellite for navigation implies some increase in complexity of instrumentation and imposes limitations on the satellite orbit. The satellite capability to track a non-radiating landmark is still an unknown, and placement of beacons on the surface would restrict the vehicle somewhat.

B. The main weakness of the system is the difficulty in instrumentation of the vehicle reference (X) frame.

There are serious difficulties with gyro platforms because of vehicle motion; the proposed sun-star-local vertical system has geographic limitations and limited movement capability because of the local vertical sensor; body-bound gyro frames are computationally and operationally still prohibitive. This basic X-frame is essential for a great many vehicle functions and should therefore receive increased attention in any further studies of this nature.

C. The complexity of the system implies a rather sophisticated computer and master logic center with attendant possibilities of impasse, singularities, or other conflict. The design of decision criteria would suffer from lack of data. Much of the equipment must be checked out on earth and emperical data obtained to refine the knowledge of the errors mentioned in section 11.

D. The meridian transit scheme is weak in that it can only be used once each day.

This work provides only a first step toward development of this system to the point of detailed comparision with other systems. It does, however, provide a framework in which systems which are totally self-contained. (onboard the vehicle), may be compared with those which involve use of the satellite or earth. It shows that the navigation schemes are profoundly influenced by the mission design and vice versa. For example, if the vehicle is to stop frequently for scientific work, the navigation system can also make good sightings about the local vertical, but if the vehicle is to move continuously some better reference will be needed. It raises questions concerning the nature of the desired exploration. For example, if previous mission photographs give sufficient detail, the vehicle may be sent to the general vicinity of target areas by latitude and longitude without any need for the satellite to locate the target for the vehicle. The paper shows that maintaining a vehicle reference frame on the surface of Mars for use in three-dimensional navigation may require some major advances in the state of the art; motions are too slow and large for accelerometers, there is too much vibration for smooth sensing of local vertical, and observations of celestial bodies have obstacle and atmospheric problems. Another contribution is the ordered listing of many of the basic sources of error in typical instrumentation systems.

In conclusion then, it is hoped that this work may provide a proper foundation from which other members of the NASA research team at R.P.I. may pursue the primary navigation system to a detailed proposal for inclusion in this country's planned exploration of the planet Mars.

LITERATURE CITED

1. NASA GRANT NGR 33-018-091 to School of Engineering, Rensselaer Polytechnic Institute, Troy, N. Y.

2. Janosko, R. E., "Primary Navigation System for an Unmanned Martian Roving Vehicle", R.P.I., Troy, New York 1970

3. Chen, H. M., "Surface Navigation System", R.P.I., Troy, N. Y., 1970

4. Micheaux, C. M., "Handbook of the Physical Properties of Mars"(NASA SP3030), Supt. of Documents, U. S. Government, 1967 p. 104.

5. Moore, J. W., "Computer System Requirements for an Autonomous Martian Roving Vehicle", AIAA Aerospace Computer Systems Conference (No.69-980) Los Angeles, Calif. 1969 p.7

6. Moore, J. W., IBID. p. 3

7. Janosko, R. E., and Shen, C. N.,"Consecutive Tracking of Landmarks: By and Active Satellite and Then by a Martian Roving Vehicle", Troy, New York, Rensselaer Polytechnic Institute, 1969.

8. Levine, G. M., "A Method of Orbital Navigation Using Optical Sightings to Unknown Landmarks", AIAA Journal, Vol., 4, No. 11, Nov.1966.

9. Battin, R. H., "Astronautical Guidance", McGraw-Hill, New York,1964,p.18.

10. Micheaux, C. M., IBID. p.31

11. de VaucouLevrs, "Icarus-International Journal of Solar System Studies", 3, 243, Academic Press, New York, 1964.

12. Gruenberg, Elliot L., "Handbook of Telemetry and Control", McGraw-Hill, New York, 1967 p. 14-34.

13. Hedge, L. and Shen, C. N., "Reference Coordinate System for Surface Navigation", R.P.I., Troy, New York 1970.

14. Chen, H. M. IBID. p-5.

15. Gruenberg, E. L., IBID, p.14-34

16. Micheaux, C. M., IBID, p. 26

17. Micheaux, C. M., IBID, p-140

18. Micheaux, C. M., IBID, p-25

19. Bekker, M. G., "Introduction to Terrain-Vehicle Systems", University of Michigan Press, Ann Arbor, Mich. 1969.

20. Rayfield, W.P. and Sandor, G. N., "Dragster On Mars", ASME News, (Hudson-Mohawk Section) Schenectady, N.Y., Feb. 1970.

21. Bundorf, R. T., "A Primer on Vehicle Directional Control"(GM A-2730), General Motors Technical Center, Warren, Mich., 1968 p-7.

22. Dutton, B., "Navigation and Nautical Astronomy", U. S. Naval Institute, Annapolis, Md., 1932

23. Micheaux, C. M., IBID., p-32

24. Anderson, E. W., "Principles of Navigation", American Elsevier, New York, 1966, p-7

25. Moore, J. W., IBID., p-13

26. Viking Project Management, "Viking on Mars", AIAA Journal, Nov. 1969,p-49

APPENDIX I

A Proposed Local Vertical Sensor

1. Background

Current plans for the primary reference frame in the Martian rover require a sensing of the local vertical direction, (magnitude not required), and also require a capability to continuously relate this unit vector to the body frame and thereby to several other possible frames. Research to date indicates no such instrument exists in a form useable by the vehicle. In order to complete an instrumentation study of the proposed X-frame, the author has designed a hypothetical device which may meet the requirements of the navigation system and will use the designed accuracy of this device for all future calculations in the error analysis. Detailed characteristics of this proosed local vertical sensor follow.

2. Desired Features

a. Sense local vertical direction, (magnitude of gravity not required), with accuracy comparable to other sensors in the system, such as star or sun trackers.

b. Provide direct electronic indication of coordinates of local vertical unit vector in body frame.

c. Be as small, light and simple as possible with minimum supporting hardward.

d. Be highly reliable, with smooth data output. Be insensitive to extraneous vehicle vibrations.

e. No singularities over a wide range of vehicle orientations.

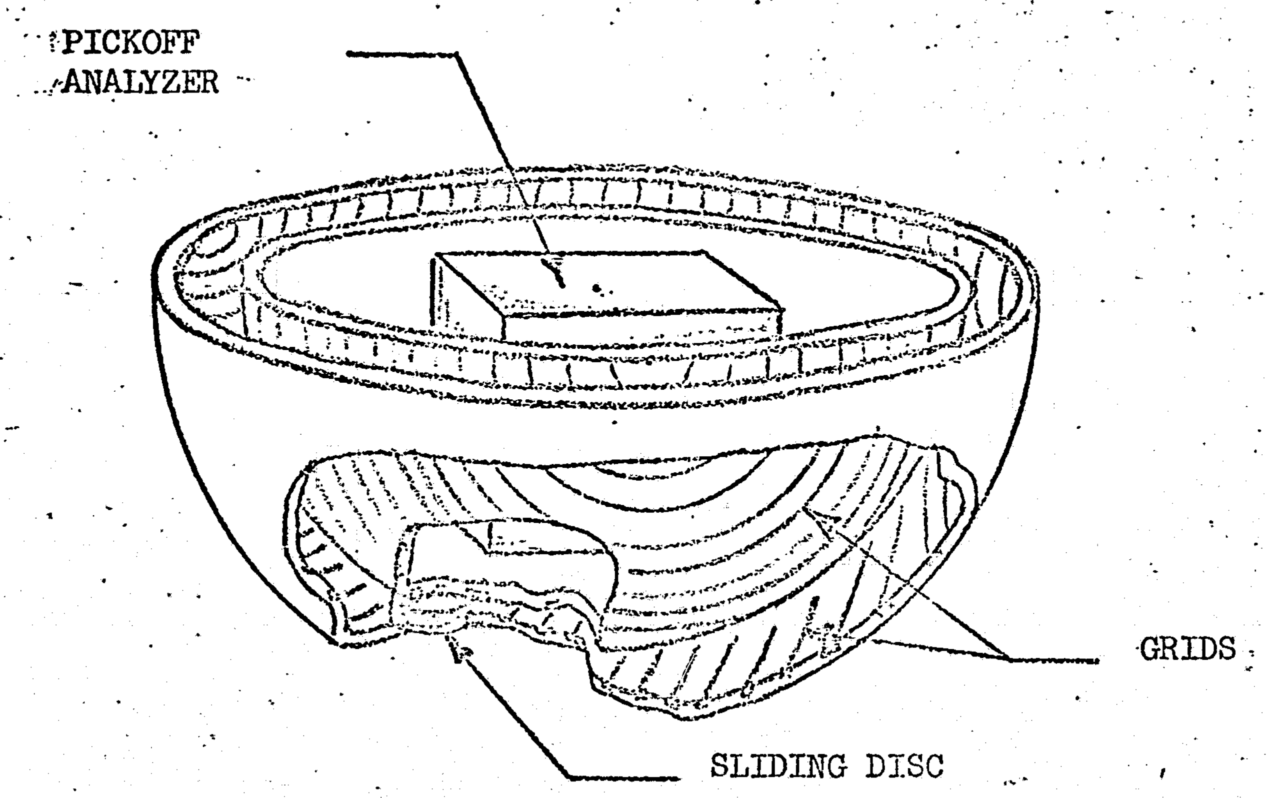


figure (12) Local Vertical Sensor

5. Resolution

The resolution of the grids is equal to the spacing δ divided by radius R, or about

$$\frac{\delta}{R} = \frac{.01 \text{ inches}}{10 \text{ ''}} = 10^{-3} \text{ radius} = 2.08 \text{ sec. of arc (vehicle stopped)}$$

With the noise smoothed, the output could hopefully be made confident to within about 10 sec. of arc or ≈ 5 milliradians, which is as good as any of the other sensors being used in the system.

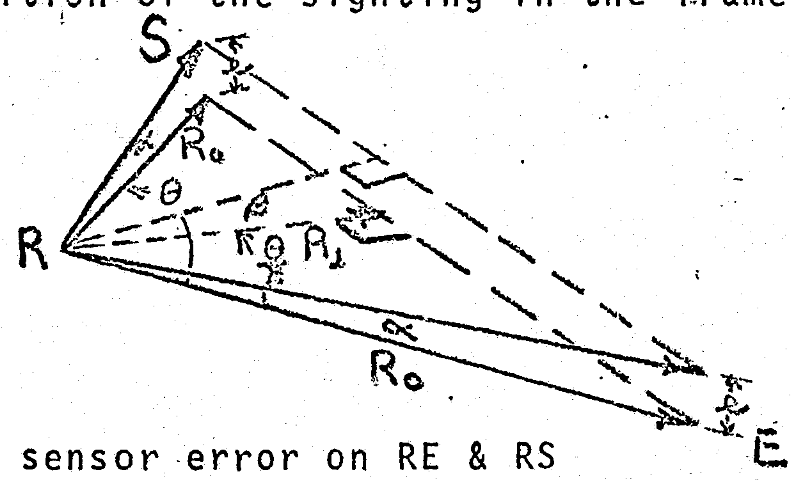
6. Conclusion

This device meets all the requirements sent forth in paragraph 2 except possibly the sensitivity to vibration, but this requires a full study of the system model, and would require some definite information on expected vehicle acceleration and vibrations before an optimum damping could be established. Otherwise, the device appears feasible and will be used as a model until a replacement is available.

APPENDIX II

REFERENCE FRAME LIMITATIONS

The basic frame inaccuracy is a function of two variables: sensor accuracy $\underline{\alpha}$, and the angle $\underline{\theta}$ between the observed vectors, $\overline{SE}$ to $\overline{SR}$ or $\overline{RE}$ to $\overline{RS}$. The optimum situation occurs when the observed vectors are perpendicular, and all accuracy is lost as they approach parallel or anti-parallel. The area of greatest inaccuracy for any observation within such a frame occurs along the bisector of $\underline{\theta}$ as in the figure below. Hence, the total accuracy of vector information sensed in this frame is a function of the frame accuracy and the position of the sighting in the frame.



$$\text{Tan } \alpha = \frac{e}{R_0}$$

$$\text{Tan } \beta = \frac{e}{R_1}$$

$$\frac{\text{Tan}\beta}{\text{Tan}\alpha} = \frac{R_0}{R_1} = \text{Sec } \frac{\theta}{2}$$

$$\therefore \beta = \text{Arc tan(Tan sec } \frac{\ }{2})$$

α = sensor error on RE & RS

β = error of bisecting vector

Some representative data are shown below.

$\alpha = 3°$

θ	β
90°	4.2°
120°	6.0°
160°	16.8°
168°	26.8°

$\alpha = .6°$

θ	β
90°	.84°
120°	1.20°
160°	3.46°
168°	5.80°